

AFFDL-TR-75-92

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## DUAL PLATE SPECKLE PHOTOGRAPHY

*STRUCTURAL INTEGRITY BRANCH  
STRUCTURES DIVISION*

OCTOBER 1975

TECHNICAL REPORT AFFDL-TR-75-92  
FINAL REPORT FOR PERIOD SEPTEMBER 1974 to MARCH 1975

Approved for public release; distribution unlimited

AIR FORCE FLIGHT DYNAMICS LABORATORY  
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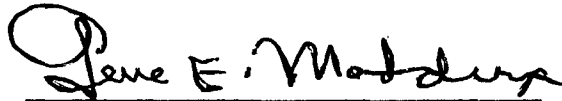
This report is the result of an in-house effort conducted under Project 1367 "Structural Integrity of Military Aerospace Vehicles," Work Unit 13670327, "Application of Photomechanics to Experimental Structural Analysis." Experimental work was performed in the Air Force Flight Dynamics Laboratory Photomechanics Facility.

This report has been reviewed by the Information Office (IO) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.



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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFFDL-TR-75-92	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle)  DUAL PLATE SPECKLE PHOTOGRAPHY		5. TYPE OF REPORT & PERIOD COVERED FINAL September 1974 to March 1975
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s)  Frank D. Adams and Gene E. Maddux		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Flight Dynamics Laboratory (AFFDL/FBR) Air Force Systems Command Wright-Patterson AFB, Ohio 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1367 136703 13670327
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Flight Dynamics Laboratory (AFFDL/FBR) Air Force Systems Command Wright-Patterson AFB, Ohio 45433		12. REPORT DATE October 1975
		13. NUMBER OF PAGES 26
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report)  Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release, distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Speckle Speckle Photography Holography Holographic Interferometry Displacement Measurements		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)  A method for measuring in-plane displacement using two laser speckle photographs is described. The technique allows the user to cancel rigid body translation and rotation. This increases the measurement accuracy of relative displacements associated with load induced strains.		

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## FOREWORD

This report is the result of an in-house effort conducted under Project 1367 "Structural Integrity of Military Aerospace Vehicles," Work Unit 13670327 "Application of Photomechanics to Experimental Structural Analysis." The experimental work was performed in the Air Force Flight Dynamics Laboratory Photomechanics Facility.

The work reported herein was conducted from June 1974 to March 1975 by Dr. Frank D. Adams, a physicist and Mr. Gene E. Maddux, an aerospace engineer both in the Fatigue, Fracture and Reliability Group, Structural Integrity Branch, Structures Division, Air Force Flight Dynamics Laboratory.

The authors wish to thank Mark R. Lenci, a cadet at the USAF Academy for obtaining preliminary data on the technique described during his summer research program at this laboratory.

This manuscript was released by the authors in September 1975.

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# LIST OF SYMBOLS

$C$	Constant (Defined in Text)
$\mathcal{F}\{g(x)\}$	Fourier Transform of Function $g(x)$
$I$	Intensity of Light
$R_{(x,y)}$	Intensity Distribution or Amplitude Transmission Function
$S$	Distance from Point in Aperture to Point of Observation
$S_o$	Distance from Origin to Point of Observation
$u$	Scalar Amplitude (Fraunhofer Diffraction Integral)
$w$	Aperture Function
$b$	Separation Distance in $z$ Direction
$e$	Exponential
$g(x)$	Arbitrary Function
$i$	$\sqrt{-1}$
$k$	$2\pi/\lambda$
$n$	Integer 1, 2, 3 . . .
$x, y, z$	Spatial Coordinates
$\Delta$	Separation Distance or Displacement
$\delta$	Dirac Delta Function
$\lambda$	Wavelength of Light
$\theta$	Angle in $x$ - $z$ Plane (see text)
$\phi$	Angle in $y$ - $z$ Plane (see text)
$\omega_1$	$k \sin \theta$
$\omega_2$	$k \sin \phi$

## SUMMARY

A method for measuring in-plane displacement using two laser speckle photographs is described. The technique allows the user to cancel rigid body translation and rotation. This increases the measurement accuracy of relative displacements associated with load induced strains.

The technique involves making separate speckle photographs of a test specimen. One is made with no load on the specimen (no displacement); the second is made with the specimen loaded (strained). A sandwich is constructed from the two speckle photographs and data are recovered in a manner similar to that used with conventional speckle photography. However, the fringes generated during data recovery are not strictly Young's fringes. Therefore a curvature of various degrees is encountered. A method of interpreting the fringe pattern is described fully in the text.



## SECTION I

### INTRODUCTION

Laser speckle photography has emerged in recent years as a proficient technique for measuring small, in-plane displacements (References 1, 2, and 3). It is particularly useful for determining the detailed characteristics of displacement or strain fields in a small area. For example, the local displacement field near a tapered shank interference fit fastener has been measured using this new technique (Reference 4).

Accurate determination of strain from displacement field measurements requires better than average precision because of the differentiations involved. This becomes particularly difficult when rigid body displacements are present. The objective of this report is to present and discuss a new method of using speckle photography which allows for the introduction of arbitrary amounts of rigid body in-plane displacement and rotation. This provides the user with an opportunity to cancel rigid body movements of a test specimen and thereby significantly increase the accuracy of relative displacement measurements obtained within a local area.

The new technique is called "Dual Plate Speckle Photography". The basic idea is by no means novel and has probably occurred to others. However, there are some fundamental and experimental problems involved which will be discussed in the text. The incentive to develop this technique was provided by Dr. Nils Abramson from the Royal Institute

of Technology, Stockholm, Sweden. During his visit to the Air Force Flight Dynamics Laboratory in April 1974, he discussed in detail the experimental methods he developed for doing "Sandwich Holography" (Reference 5).

In Section II, basic elements of speckle photography are briefly reviewed. Two of the appendixes support the material presented in this section and are recommended reading for those not previously exposed to these ideas. Dual plate speckle photography is described in Section III. A mathematical model is developed to explain the fringe pattern one observes in the diffraction halo of a dual plate specklegram. Also some experimental data are provided.

## SECTION II

### BASIC SPECKLE PHOTOGRAPHY

The speckled appearance of a diffuse surface illuminated by laser light is easily recorded using high resolution photographic film. If a double exposure is made of an object with some in-plane displacement occurring between exposures, then each speckle will be recorded twice. The distance between each speckle pair is a direct measurement of the in-plane vector displacement. The photographic film plate on which such a recording is made is usually called a "specklegram".

Displacement data are recovered from a specklegram by passing a narrow collimated laser beam through the photographic image. High spatial frequencies in the speckle pattern cause diffraction and part of the laser beam diverges into a cone called the diffraction halo. Since the speckles occur as equally spaced pairs in an otherwise random pattern, the diffraction halo will be modulated by Young's fringes. These fringes will have a spacing which is inversely proportional to the speckle pair separation and perpendicular to it's direction. Thus, displacement magnitude and direction can be measured at any location on the image by passing a narrow collimated laser beam through that point. Figure 1 illustrates the basic recording and data readout technique. For more detailed information concerning speckle photography, the reader is referred to Reference 3.

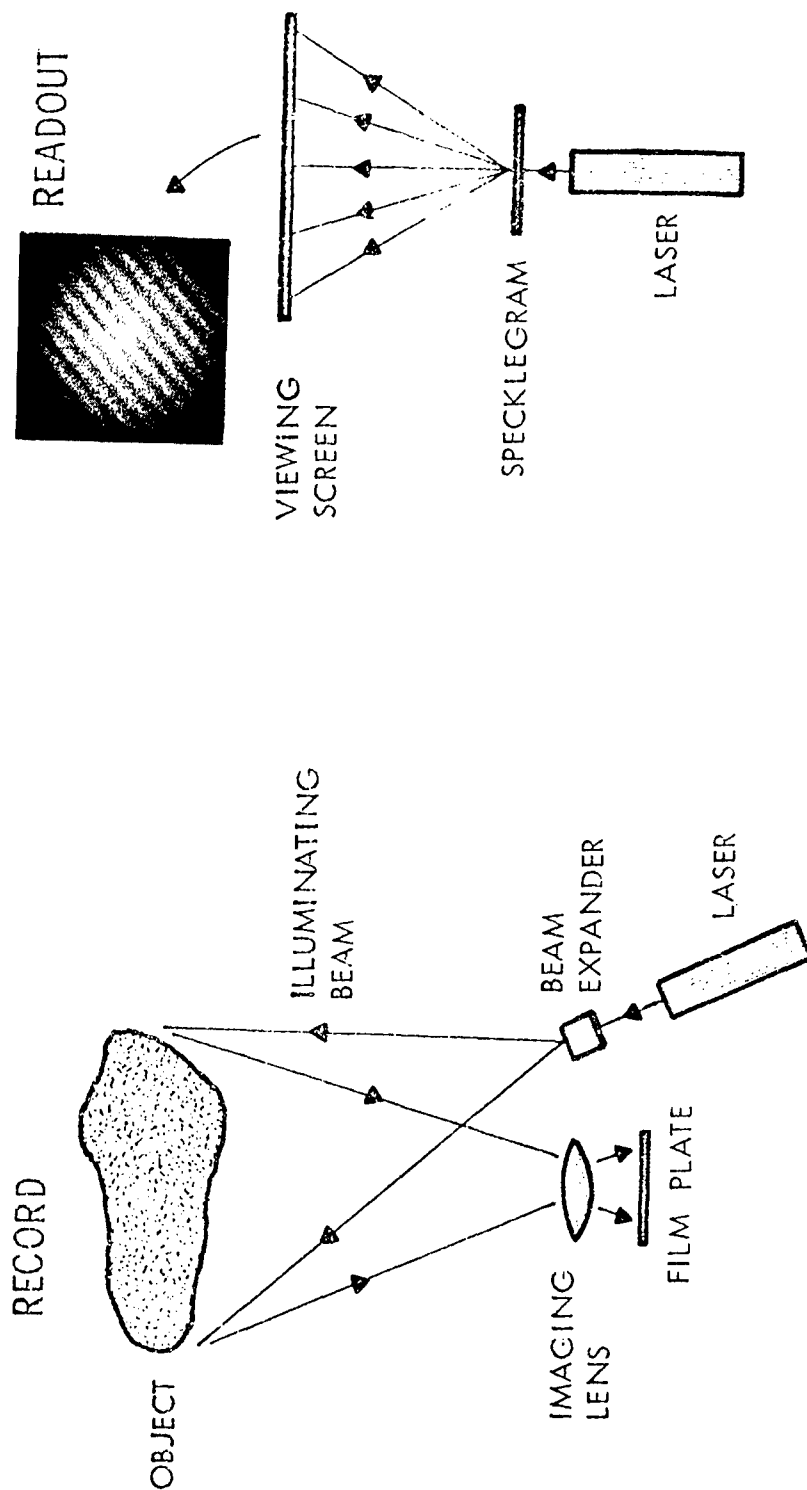


Figure 1. Specklegram Recording and Data Readout Techniques

The generation of Young's fringes in the diffraction halo is predicted by scalar wave theory. The calculation is closely related to a Fourier transform. A brief sketch of a mathematical model is presented in Appendixes A and B.

### SECTION III

#### DUAL PLATE SPECKLE PHOTOGRAPHY

In order to cancel the effect of rigid body in-plane movement of a specimen when using conventional speckle photography, the film holder must be translated or rotated between exposures by a corresponding amount. An alternative procedure would be to induce an opposite but equal movement of the image by some optical means. In either case, prior knowledge of the amount of rigid body movement is required.

Dual plate speckle photography offers the user a method of canceling rigid body movements without a prior knowledge of the magnitude. Instead of employing a double exposure technique, two separate speckle photographs are made. The film plates are then sandwiched together and data recovery is accomplished as with a conventional specklegram. In-plane rigid body translation or rotations are canceled by moving one film plate with respect to the other. This allows small changes in relative displacement as a function of position to be accurately measured.

With a conventional double exposure specklegram, in-plane displacements result in speckle pairs contained in a plane perpendicular to the optical axis. This geometry is not completely simulated by the dual plate technique. Film emulsions are not infinitely thin and glass plates vary in thickness. As a result, each speckle of a pair will be recorded either forward or behind its partner. This is true even when the recordings are made such that the sandwiches are put together emulsion to emulsion. This

situation has fundamental implications in both the recording and recovery of speckle data. Each of these will be discussed in some detail.

The following procedure is employed to record a dual plate specklegram. A glass film plate (we typically use Agfa 10E75) is sandwiched with a clear plate of glass placing the emulsion side towards the center of the sandwich. A speckle photograph is made of the undisplaced object with the film plate on the lens side of the sandwich. Then, second speckle photograph is made of the displaced object using a second identical sandwich except that it is turned around so that the clear glass plate is positioned towards the lens. Both film plates are then processed and thoroughly dried. A dual plate specklegram is constructed by placing the two speckle photographs emulsion to emulsion such that the images are geometrically matched. A holding device to accomplish this task is highly recommended. Figure 2 is a photograph of a dual plate holder which provides for translation or rotation of one speckle photograph with respect to the other. A description of this device is provided in Appendix C.

There are two fundamental limitations in the recording method previously described. Both are related to the fact that the emulsions on each film plate may be in slightly different planes when the exposures are made. First, laser speckles are three-dimensional entities in the image plane. The two-dimensional speckle pattern decorrelates in a distance which is small compared to the conventional depth of field for an imaging lens system (References 2 and 6). Decorrelation is particularly severe with lens apertures wider than about  $f/4$ . This problem can be

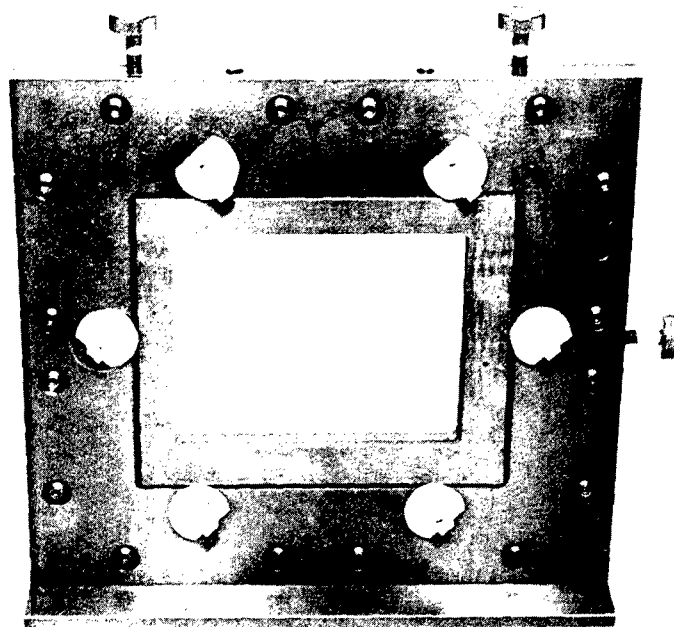


Figure 2. Holding Device for Dual Plate Speckle Photography



reduced by increasing image magnification. Second, even within the speckle correlation distance, a small change in magnification occurs with image position. This causes a radial shift of speckle position for image points off of the optical axis. During data recovery, this will induce apparent in-plane displacement fringes. This phenomena is closely related to the apparent in-plane displacement fringes that are generated with a conventional specklegram when out-of-plane displacements of the object have occurred between exposures (References 2 and 6). This problem can be minimized by using imaging lenses with long focal lengths.

Data recovery from a dual plate specklegram is also complicated by the longitudinal displacement of paired speckles due to separate emulsions. The fringes modulating the diffraction halo are found to be curved in various degrees. Typical patterns are shown in Figure 3. These photographs suggest that a modification of the Young's equations derived in Appendixes A and B are required in order to interpret these fringes and acquire displacement data.

The Fraunhofer diffraction integral introduced in Appendix A is restricted to apertures contained in the  $x-y$  plane at  $z=0$ . A physical interpretation of Eq. (A-1) is that it represents a summation of Huygen's wave amplitudes at an arbitrary observation point. The Huygen's wave source points are contained in the aperture. These are temporally coherent since it is assumed that the aperture is backlighted with a plane wave at normal incidence.

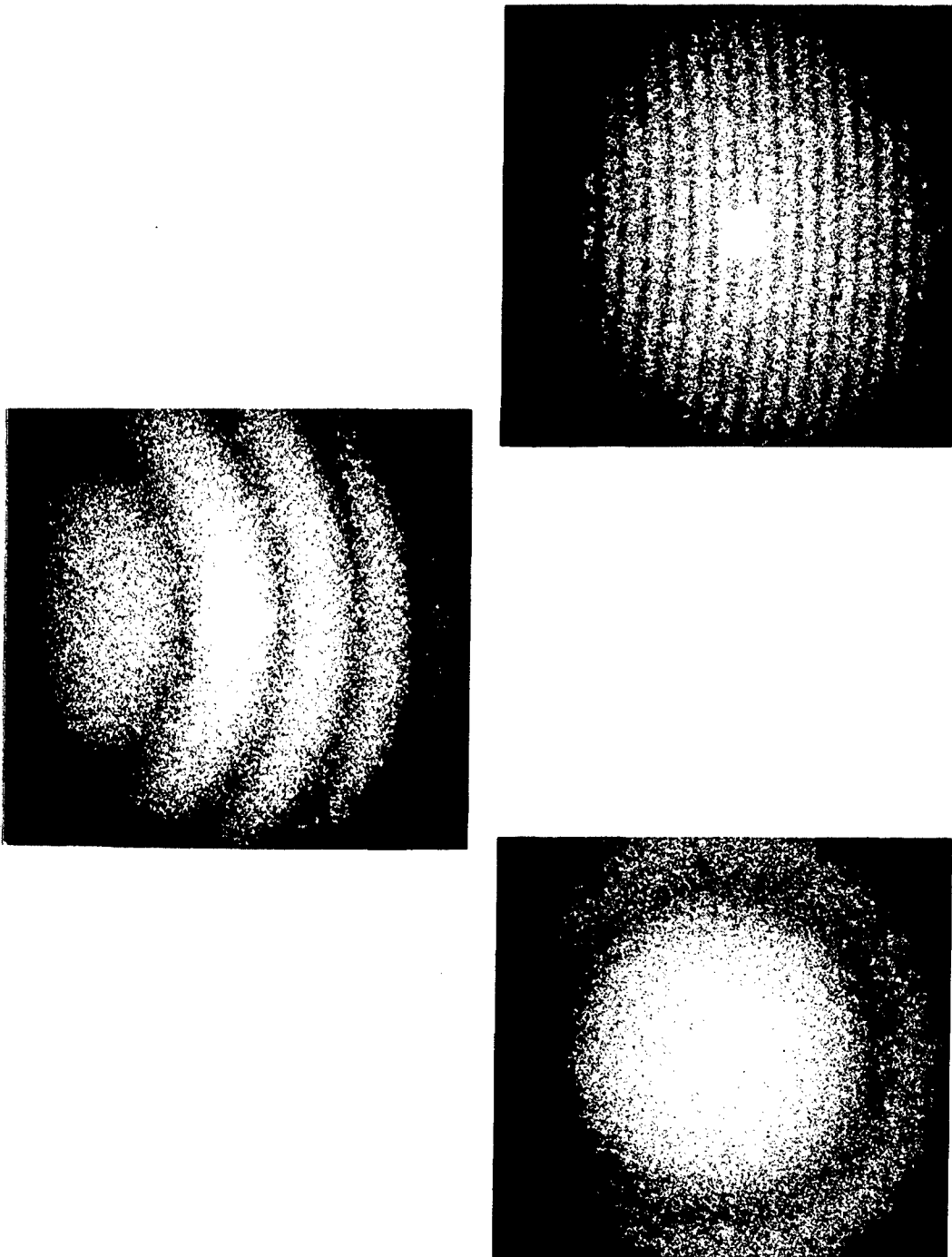


Figure 3. Typical Fringe Patterns

Now interference phenomena in the diffraction halo are primarily dependent on the phase summation and, therefore, on the aperture to observation point distance given by Eq. (A-2). If source points in the aperture occurs for  $z \neq 0$ , it is this expression that requires modification. Two changes are necessary. First, the source point to observation point distance is decreased by approximately  $z (\cos \theta + \cos \phi - 2)$ . Second, the radiative phase of the source points are now a function of  $z$ . This can be accounted for by increasing the path length by a distance equal to  $z$ . The modified expression to replace Eq. (A-2) is, therefore,

$$S = S_0 - x \sin \theta - y \sin \phi - z (\cos \theta + \cos \phi - 2) \quad (1)$$

One further change is required. In Appendixes A and B, planar apertures allow summations to be performed with an area element  $dx dy$ . With source points at  $z \neq 0$ , the area element can be a function of  $x, y$  and  $z$ . For an aperture consisting of two or more pinholes represented by three-dimensional Dirac delta functions, a volume element  $dx dy dz$  is appropriate.

With the above modification, the fringe pattern for a dual plate specklegram is easily derived. Let a speckle pair be represented by an aperture  $W$  given by

$$W = \delta(x - \frac{A}{2}, y, z + \frac{b}{2}) + \delta(x + \frac{A}{2}, y, z - \frac{b}{2}) \quad (2)$$

The in-plane displacement  $\Delta$  is taken in the  $x$  direction. The longitudinal separation  $b$  models the situation of each speckle being in a different emulsion plane.

Following the procedure outlined in Appendix B - Case I, an expression for the intensity  $I$  is obtained.

$$I \propto 1 + \cos[\Delta k \sin \theta + bk(2 - \cos \theta - \cos \phi)] \quad (3)$$

Examination of Eq. (3) reveals a set of curved fringes of the type shown in Figure 3.

Three features about Eq. (3) should be noted immediately. First, if  $b=0$ , Eq. (3) and Eq. (B-3) are identical and Young's fringes are seen. If  $\Delta \gg b$  this situation is closely approached and fringes similar to those in the top photograph of Figure 3 are obtained. Secondly, if  $\Delta$  and  $b$  are of nearly equal magnitude, the pattern is substantially altered. The  $[bk \cos \phi]$  term causes curvature; the  $[bk \cos \theta]$  term modifies the spacing. A typical pattern is shown in the center photograph of Figure 3. Finally, if  $\Delta=0$  the fringe function approximates a set of concentric circles. The spacing between these circles is inversely proportional to  $b$ . The bottom photograph in Figure 3 illustrates this pattern.

The previous discussion indicates that although data recovery is somewhat complicated by the longitudinal separation  $b$  of paired speckles, all of the information needed to measure the in-plane displacement  $\Delta$  is present. The following procedure is typical. First, the value of  $b$  is

measured by translating one speckle photograph with respect to the other until the pattern shown in the lower photograph in Figure 3 is obtained. Fringe minima of order  $n$  are then related to  $b$  by the equation

$$b = \frac{(n - \frac{1}{2}) \lambda}{(2 - \cos \theta - \cos \phi)} \quad (4)$$

Because of circular symmetry, Eq. (4) reduces to

$$b = \frac{(n - \frac{1}{2}) \lambda}{(2 - \cos \theta)} \quad (5)$$

Relative values of in-plane displacement  $\Delta$  can now be acquired at any point on the image. The value of  $\Delta$  at the point used to measure  $b$  is taken as zero. All other image points will produce fringe patterns with minima of order  $n$  related to  $\Delta$  by the equation

$$\Delta = \frac{(n - \frac{1}{2}) \lambda - b(2 - \cos \theta - \cos \phi)}{\sin \theta} \quad (6)$$

If measurements are secured along the symmetry line defined by  $\phi = 0$ , Eq. 6 reduces to

$$\Delta = \frac{(n - \frac{1}{2}) \lambda - b(1 - \cos \theta)}{\sin \theta} \quad (7)$$

A study of Eqs. (6) and (7) reveals several subtle properties. Note, for example, that for positive values of  $n$ , a negative value of  $\theta$  would

appear to yield a negative value of  $\Delta$ . This is not a valid interpretation. Negative values of  $\Theta$  correspond to negative interference orders.\* The sign of  $\Theta$  can be determined from the diffraction halo fringe pattern. Positive values of  $\Theta$  sweep the observation point away from the center of curvature (to the right on the center photograph in Figure 3).

The sign complications discussed previously are not present when data are read from a conventional double exposure specklegram. This is because Young's fringes are symmetrical, and therefore, the direction of displacement is undeterminable. Without some external information, it is not possible to know which speckle in a given pair was recorded first.

With dual plate speckle photography, displacement direction becomes determinable. This information is contained in the curvature of the fringes. If the front plate in the dual plate specklegram is a recording of the undisplaced object, the relative displacements suffered by the image recorded on the rear plate are in a direction pointing away from the center of curvature (positive values of  $\Theta$ ).

\*Positive orders are denoted by  $n = 1, 2, 3 \dots$ . The first negative order minimum occurs for  $n = 0$ , the second negative minimum occurs for  $n = -1$ , etc.

## APPENDIX A

### FRAUNHOFER DIFFRACTION INTEGRAL

Consider an aperture  $w$  of finite extent illuminated from behind by a collimated laser beam (a monochromatic plane parallel light wave). The far field intensity distribution of diffracted light is closely related to the Fourier transform integral (Reference 7). In particular the intensity  $I$  is proportional to a scalar product  $u u^*$  where  $u$  is the Fraunhofer diffraction integral.

$$u = \int_w dx dy \frac{e^{i k S}}{S} \quad (\text{A-1})$$

Equation (A-1) represents a summation over an aperture  $w$  contained in the  $x$ - $y$  plane at  $z=0$ . The wave number  $k$  is  $2\pi$  divided by the wavelength and  $S$  is the distance from a point in the aperture to the point of observation.

The validity of Eq (A-1) is restricted to small angle diffraction so that if the origin is located near the center of the aperture

$$S \approx S_0 - x \sin \theta - y \sin \phi \quad (\text{A-2})$$

where  $S_0$  is the origin to observation point distance. The angles  $\theta$  and  $\phi$  are projections into the  $x$ - $z$  and  $y$ - $z$  planes respectively of the inclination of the ray  $S_0$  from the  $z$  axis (See Figure 4). The coordinates  $x$  and  $y$  locate source points in the aperture  $w$ . Therefore, (A-1) can be approximated by

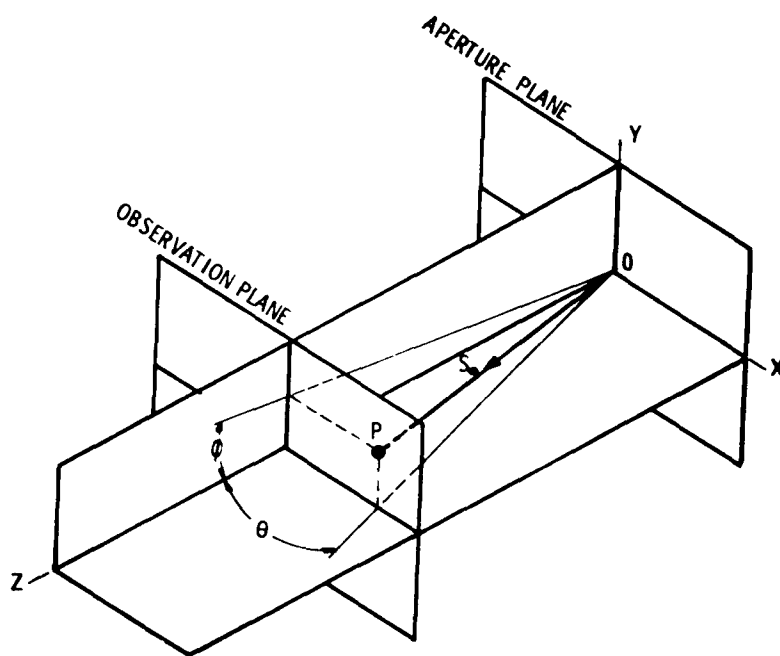


Figure 4. Sketch Defining Angles  $\theta$  and  $\phi$



$$u = \frac{e^{ikS_0}}{S_0} \int_W dx dy e^{-ik(x \sin \theta + y \sin \phi)} \quad (\text{A-3})$$

Within a multiplicative constant Eq (A-3) is a two-dimensional Fourier transform of the aperture  $W$ . The spatial variables are  $x$  and  $y$ . The frequency variables are  $\omega_1 = k \sin \theta$  and  $\omega_2 = k \sin \phi$ , thus

$$u = c \mathcal{F}\{W(x, y)\} \quad (\text{A-4})$$

where

$$\mathcal{F}\{W(x, y)\} \equiv \frac{1}{2\pi} \int_W dx dy e^{-i(\omega_1 x + \omega_2 y)} \quad (\text{A-5})$$

The constant

$$c = 2\pi \frac{e^{ikS_0}}{S_0}$$

## APPENDIX B

### YOUNG'S FRINGES

The equations developed in Appendix A are used here to calculate the intensity distribution for two different apertures. For the first case the aperture is two small pinholes. The resulting diffraction pattern is shown to be the classical Young's fringes. The second calculation models the aperture as a small area in a double exposure specklegram illuminated by a collimated laser beam. The result is a random diffraction halo modulated by Young's fringes.

Case I - Two Pinholes. Consider the aperture  $W$  to be two very small pinholes separated by a distance  $\Delta$ . This aperture can be modeled by the summation of two Dirac delta functions of the form  $\delta_{(x-x_0, y-y_0)}$

Thus

$$u = c \mathcal{F}\{\delta_{(x-\Delta/2, y)} + \delta_{(x+\Delta/2, y)}\} \quad (B-1)$$

Evaluation of the Fourier transform yields

$$u = 2c \cos\left(\frac{\Delta}{2} \omega_x\right) \quad (B-2)$$

Now the intensity  $I$  is proportional to  $uu^*$  thus

$$I \propto 1 + \cos(\Delta \omega_x) \quad (B-3)$$

or

$$I \propto 1 + \cos(\Delta k \sin \theta)$$

Equation (B-3) is the intensity distribution for Young's Fringes. By using  $k = 2\pi/\lambda$  where  $\lambda$  is the wavelength and noting that minima occur for  $\cos(\Delta k \sin \theta) = -1$ , the conditions for fringe minima are

$$(n - 1/2) \lambda = \Delta \sin \theta \quad (\text{B-4})$$

$$n = 1, 2, 3 \dots$$

Case II - Specklegram. Before calculating the diffraction pattern from a double exposure specklegram, first consider a single exposure photographic transparency of an object illuminated by laser light. The recorded image is, of course, speckled. If a small diameter laser beam is passed through a portion of the transparency, the aperture  $w$  will be the amplitude transmission function  $R_{(x,y)}$  inside the illuminated area. Thus

$$u_o = c \mathcal{F}\{R_{(x,y)}\} \quad (\text{B-5})$$

and

$$I_o \propto \mathcal{F}\{R_{(x,y)}\} \mathcal{F}^*\{R_{(x,y)}\} \quad (\text{B-6})$$

Equations (B-5) and (B-6) can be evaluated to some extent since the statistical properties of the speckle pattern  $R_{(x,y)}$  are known (Reference 8). This will not be done because the objective here is simply to obtain representative expressions for the diffraction halo. Equations (B-5) and (B-6) are these expressions and are denoted by the zero subscript.

Now, for a double exposure photographic transparency (speckle-gram) where the object has suffered an in-plane displacement  $\Delta$  in the  $x$  direction between exposures, the amplitude transmission function is

$$R_2(x, y) = R_{(x-\Delta/2, y)} + R_{(x+\Delta/2, y)} \quad (\text{B-7})$$

A series expansion of Eq (B-7) yields

$$R_2(x, y) = 2 \left[ R_{(x, y)} + \frac{R''_{(x, y)}}{2!} \left( \frac{\Delta}{2} \right)^2 + \frac{R''''_{(x, y)}}{4!} \left( \frac{\Delta}{2} \right)^4 + \dots \right] \quad (\text{B-8})$$

where primes indicate differentials with respect to the variable  $x$ .

The linear properties of a Fourier transform provide that

$$\mathcal{F}\{g^{(n)}_{(x)}\} = (i\omega_1)^n \mathcal{F}\{g_{(x)}\} \quad (\text{B-9})$$

where  $g^{(n)}_{(x)}$  is the  $n$ th derivative of a function  $g_{(x)}$ . Thus

$$u = c \mathcal{F}\{R_2(x, y)\}$$

$$u = c \mathcal{F}\{R_{(x, y)}\} 2 \left[ 1 - \frac{1}{2!} \left( \omega_1 \frac{\Delta}{2} \right)^2 + \frac{1}{4!} \left( \omega_1 \frac{\Delta}{2} \right)^4 + \dots \right]$$

$$u = c \mathcal{F}\{R_{(x, y)}\} \left[ 2 \cos \left( \omega_1 \frac{\Delta}{2} \right) \right] \quad (\text{B-10})$$

Using Eqs (B-5) and (B-6) and  $\omega_1 = k \sin \theta$

$$\mathcal{U} = \mathcal{U}_0 2 \cos \left( \frac{\Delta}{2} k \sin \theta \right) \quad (\text{B-11})$$

and

$$I = I_0 \left[ 1 + \cos(\Delta k \sin \theta) \right] \quad (\text{B-12})$$

Thus, the intensity distribution from a specklegram is the diffraction halo from a single exposure transparency modulated by Young's fringes.

## APPENDIX C

### DUAL PLATE HOLDER

A dual plate specklegram is made by placing two speckle photographs emulsion to emulsion such that the images are geometrically matched. In-plane movement of one film plate with respect to the other is used to cancel rigid body displacements as explained in the text. A holding device to accomplish this task is described in this appendix.

A photograph of the plate holder is shown in Figure 2. This device has three main parts; a main frame, a translation stage, and a fixed plate holder. Figure 5 is a photograph of the disassembled main frame. The front and rear sections sandwich a translation stage and a center section. Screw adjustments and return springs are housed in the center section. Figure 6 is a photograph of the translation stage set within the center section. A four by five inch glass film plate is held in place by small spring clips along the edge of the "window". Figure 7 shows the fixed plate holder removed from the main frame. It too is equipped with spring clips to hold a glass film plate. This fixed plate holder was designed to be removed so as to gain access to the translation stage. This facilitates mounting and removal of film plates on both the translation stage and the fixed plate holder. The fixed plate holder is secured to the main frame by six Teflon cams. These provide adjustable pressure to the glass film plates which must slide one with respect to the other. A light silicon lubricant on the film emulsion was found to reduce friction.

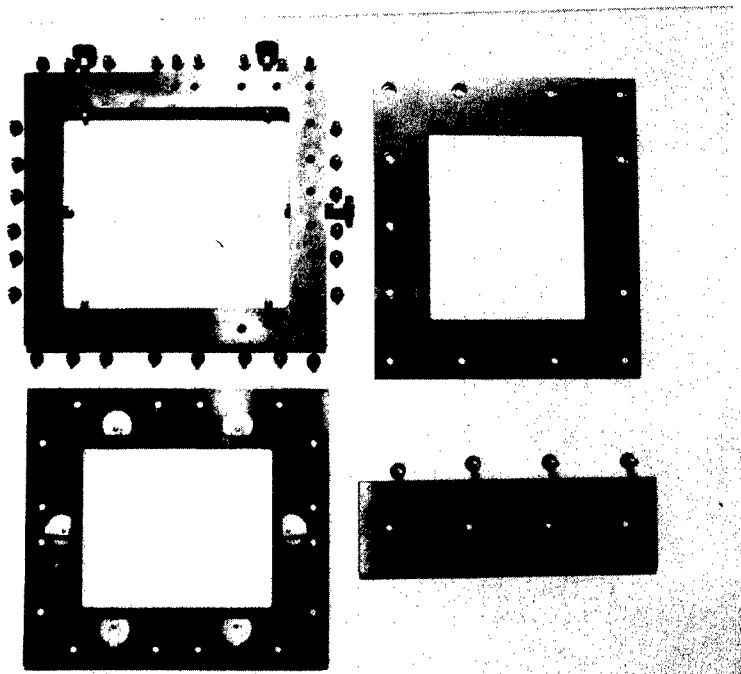


Figure 5. Disassembled Main Frame

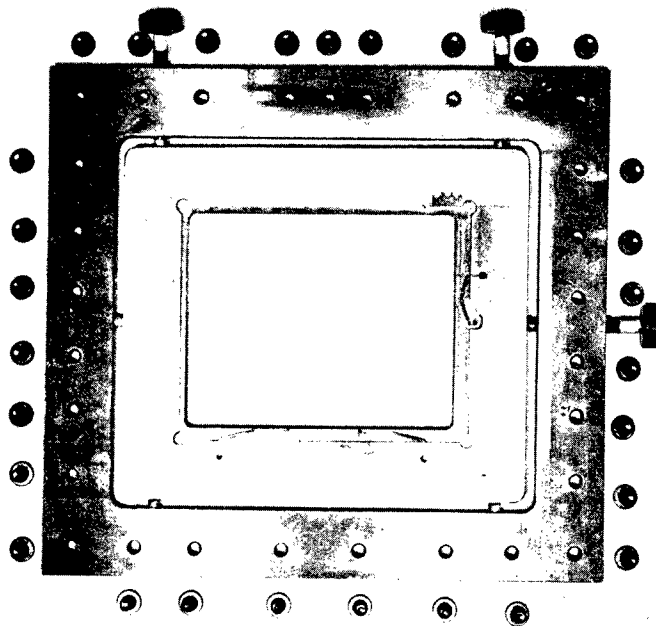


Figure 6. Translation Stage Within Center Section



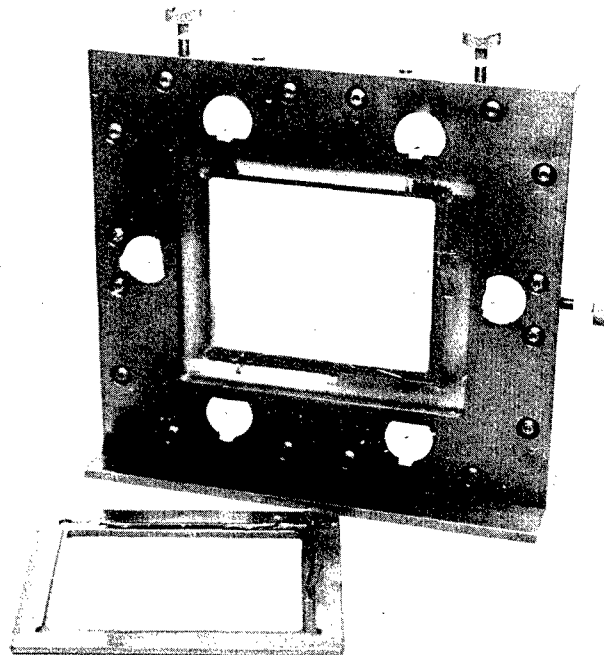


Figure 7. Holding Device With Fixed Plate Holder Removed

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